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National Aeronautics and Space Administration
Goddard Space Flight Center
Contract No. NAS-5-3760

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ELECTRON AND ION TEMPERATURE IN THE IONOSPHERE

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by T. K. Breus
& G. L. Gdalevich

SUMMARY

Contemporary theoretical representations and experimental data on temperatures of electrons T_e and ions T_i in the ionosphere are described. It is shown that the temperature equilibrium between ions and electrons is absent in the F-region of the ionosphere. Data are presented on the daily, latitude and altitude dependences of the electron temperature. Comparison of calculated and experimental values of T_e and T_i attest to the necessity of broadening the direct measurements of electron and ion temperatures and of accumulating information on such thermal sources as the electrostatic field, electromagnetic waves and fluxes of energetic particles.

* * *

The temperature, concentration and chemical composition pertain to the number of fundamental parameters characterizing the Earth's atmosphere as a whole, as well as the ionosphere. At the same time, the temperature influences to a significant degree the distribution of particle concentration with height and the subdivision of the atmosphere into regions of different chemical composition.

In reality, the distribution of charged particles with height in a quasi-neutral ($n_i = \Sigma n_j = n_e$) isothermic ionosphere, in which only singly charged ions are present, is described in the first approximation by the following laws [1]:

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$$\frac{1}{n_e}\frac{dn_e}{dz} = -\frac{m_+ g}{k(T_e + T_i)}, \qquad (1)$$

$$\frac{1}{n_j}\frac{dn_j}{dz} = -\left[m_j - \frac{m_+ T_e}{T_e + T_i}\right]\frac{g}{kT_i}, \qquad (2)$$

where n_j and n_e are respectively the concentrations of ions and electrons, $m_+ = \frac{\Sigma m_j n_j}{\Sigma n_j}$ is the mean mass of ions and T_e and T_i are respectively the electron and ion temperatures.

It is evident that the correlation between the electron and ion temperatures characterizes also the thermal balance in the ionosphere.

Temperature measurements and the ascertaining of its seasonal, latitude and altitude variations will indirectly help the estimate of the character and magnitude of thermal sources heating the Earth's atmosphere.

All this serves as convincing evidence of the importance of temperature investigations for the understanding of the physics of the ionosphere.

Such investigations are conducted by three fundamental methods :

a) direct measurements of T_e and T_i with the aid of devices raised into the ionosphere with the aid of rockets and satellites;

b) indirect methods, consisting in the determination of temperature from the data of other ionosphere investigations.

The present review will be only concerned with those indirect methods which use for initial data the material obtained from direct measurements on rockets and satellites.

Selecting in particular a specific ionosphere model and utilizing formula (1), the mean temperature $(T_e + T_i) / 2$ is found from electron and ion altitude profiles;

c) method based upon incoherent radiowave backscattering.

Inasmuch as the direct and indirect determinations of electron and ion temperatures were conducted to-date for different geographical and physical conditions, and because of strong dependence of indirect or theoretical determinations of temperatures from the assumed ionosphere model and from the knowledge of the intensity of thermal sources (such as, for example, the ultraviolet and corpuscular radiations of the Sun), the problem of correlation between the ion and electron temperatures was clarified only very recently.

Let us consider the development of theoretical representations of electron and ion temperatures in the ionosphere.

The ideas, upon which the calculation of electron temperatures are founded in all theoretical works, amount to the following: as a result of photoeffect under the action of Sun's ultraviolet radiation electrons form mainly in the 100 — 300 km altitude range, of which the energy exceeds considerably the thermal energy. These electrons lose part of their energy at collisions with surrounding gas particles. Because of substantial difference in the mass value of ions (m_j) and electrons (m_e), the energy transfer from photoelectrons to the electron gas may be realized more rapidly than to the ionic gas; that is why the mean energy, and consequently also the temperature of electrons may result greater than that of ions.

As follows from the Drukarev work [2], published as far back as 1946, in the F-layer, for which the settling time of Maxwellian distribution in the electron gas is significantly less than the loss time by photoelectrons of residual energy at elastic collisions with neutral particles and ions, the difference between the electron and ion temperatures (°K) is determined by the expression

$$T_e - T_i \approx \frac{qm_j}{n_e k m_e \nu} \varepsilon \approx 50\varepsilon, \qquad (3)$$

where ν is the collision frequency between electrons and ions, q/n_e is the ratio of the number of photoelectrons emerging in 1 cm^3 per second to the total concentration of electrons in the F-layer, and ε is the mean energy of photoelectrons in electronvolts.

According to Drukarev's estimates, ε is of the order of several eV and the difference between the electron and ion temperatures may be quite notable.

The value of ε, just as that of q, has not been determined sufficiently precisely up until now; this is one of the causes of discrepancy between the results of various theoretical calculations.

Thus, for example, lower values of ε were utilized in [3, 4] than in [2]; moreover, despite the fact that the analytical expression for T_e was similar to that obtained in [2], conclusion was derived of the existence of a temperature equilibrium in the F-layer between the ions and electrons.

Such a representation of temperature equilibrium in the ionosphere persisted through very recent times, so long as the results of experiments obtained on rockets and satellites have not led to the requirement of its reconsideration.

With the aid of rockets and satellites, data were obtained on the intensity of ultraviolet radiation I_{uv} [5 – 8], the density n and the composition of particles in the atmosphere [9 – 14], having permitted to reestimate the quantity $q = I_{uv} \sigma n$, where σ is the ionization cross section..

Fluxes of electrons ($\sim 10^8$ cm^{-2}.sec^{-1}.sterad^{-1}) with energy > 40 ev were observed in particular in the 200 – 400 km altitude range [15]; the author's assumption was that those were "fresh" photoelectrons which lacked the time to come to the state of equilibrium with the surrounding medium. Such large fluxes of energetic photoelectrons must constitute evidence in favor of high mean energy values ϵ, and consequently of absence of temperature equilibrium.

Attempts to investigate the theoretical electron and ion temperatures were again made in 1961 – 1963 [16 – 18] despite the still remaining uncertainty of numerous parameters required for a strict computation (for example I_{uv} at heights above 235 km).

All the three temperature models were based upon the assumption that the rate of local heating of electron gas and the rate of photoelectron cooling were equal at all heights. The energy losses by photoelectrons are determined by various processes, of which everyone is effective in the specific altitude interval. For example, for heights to 250 km photoelectrons decelerate to thermal velocities mainly at the expense of inelastic collisions with neutral particles attended by the ionization and excitation of the latter. At heights above 250 km the principal role in energy losses is played by elastic collisions with ions and the Coulomb interaction with electrons. Above ~ 600 km the thermal relationship between the electrons and the atmosphere diminishes on account of rapid decrease of collision frequency and the conductance of the electron gas begins to play an important role in the losses of energy.

The most complete of temperature models is the Hanson model [17], which took into account not only the local heat contribution by photoelectrons emerging in the F-layer, but also the global energy contribution above 300 km by the ultraviolet radiation on account of their diffusion along the magnetic tubes of force.

In the assumption that the energy losses by photoelectrons are determined for the heights between the F-layer and the 1000 km level by elastic collisions with O^+, the following expression was obtained for T_e [17]:

$$\frac{T - T_{neutr}}{T_e^{\,5/2}} \approx \frac{2 \cdot 10^6 Q}{n_e^2} \qquad (4)$$

where $Q = \varkappa q$, and $\varkappa$ is the part of kinetic energy of photoelectrons passing to thermal energy (of which the magnitude is, incidentally, to the greatest degree undetermined); T_{neutr} is the temperature of the neutral gas.

It followed from the Hanson computations, that in the E-region in daytime $T_e / T_i \approx 1$ (with $T_i \approx T_{neut}$); in the 250 – 300 km altitude range $T_e / T_i \approx 2.5$ and even 3, and above 300 km $T_e / T_i \approx 1.2$. At heights > 900 km, where the determinant role in particle collision is played by the Coulomb interaction, the values of the ion temperature must get nearer those of electron temperature ($T_e / T_i \approx 1$) and the ion temperature may exceed that of neutral particles ($T_i > T_{neutr}$).

This result is exceedingly interesting, inasmuch as at great heights, as will be seen further, no measurements of T_i have been performed as yet. Calculations by Hanson [17], Dalgarno et al [18] correspond to diurnal ionosphere in a period of solar activity maximum. No calculations for the night ionosphere were performed in these works, while within the framework of indicated models, temperature equilibrium must take place because of absence at night of a heating source.

One of the shortcomings of Hanson's calculations is the imprecise accounting of conductance of electron gas, as this was recently shown by Bowhill and Geisler [19], substantially influencing the altitude distribution of electron temperatures in the solar activity minimum. The authors of [19] estimate that this circumstance is precisely the one that can lead to the discrepancy between the experimental and theoretical profiles at altitudes above 200 km.

Interesting results concerning the night temperatures in the F-layer are also brought up in [19].

Bowhill and Geisler have estimated the magnitude and the velocity of heat influx from outer regions of the ionosphere and protonosphere into the F-layer, in nighttime, when the daytime source of heating — the ultraviolet radiation — is excluded and the protonosphere serves as a reservoir from which the heat, accumulated in daytime, enters the F-layer along the magnetic tubes of force. It follows from the calculations that the values of this flux are sufficient for the explanation of the heating of the night F-layer and the absence in it of temperature equilibrium.

Moreover, insamuch as the heat flux is materialized along the magnetic tubes of force, the conditions for the thermal link between the ionosphere and the protonosphere at various latitudes will be different, and a dependence of T_e and T_i on the geomagnetic latitude must be observed.

It thus becomes clear, even from such brief descriptions of the results of theoretical calculations, to what extent they require experimental material for their further development and refinement. A substantial influence on the theoretical models may also be exerted by data on other, heretofore insufficiently studied thermal sources, such as fluxes of energetic particles, electrostatic fields, hydrodynamic waves and, obviously, all the data on electron temperatures obtained by direct measurements in the first place.

Let us now pass to the description of certain results of direct measurements of T_e and T_i and consider their relationship with theoretical investigations.

First of all we shall briefly enumerate the objects and devices with the help of which were obtained the results described in the present paper. The electron temperature was measured (1960 - 1964) on Japanese (Langmuir spherical sondes) and American (dual dumb-bell type, Langmuir plane and cylindrical sondes) rockets, on satellites Explorer-8, Ariel-1 (plane sondes) Explorer-17 and Explorer-22 (cylindrical sondes).

There were on Cosmos-2 Langmuir cylindrical sondes for the measurement of electron temperature and an ion trap of the "honeycomb" type for measuring the ion temperature. It should be noted that on Cosmos-2 the ion temperatures were measured first (direct measurements). About half a year after the launching of Cosmos-2 measurements of ion temperature were carried out on American rockets with the aid of a special method utilizing a spherical ion trap. The ion temperature was also determined on the anglo-american satellite Ariel-1 launched somewhat later than Cosmos-2, by the peak width of the second collector current derivative of the spherical ion trap.

A series of data on the ratio of electron to ion temperatures T_e / T_i were obtained by the method of incoherent backscattering. This method became familiar only after appearance of the newest and very powerful highly sensitive locators. It is based upon the phenomenon of radiowave scattering on free electrons.

It was estimated at first that because of thermal velocities the energy of the received signal must be distributed in a frequency band corresponding to these velocities. However, the first experimental data [20] have shown that the scattered energy equals the forecast one, but the frequency broadening is substantially less than the anticipated. This effect was explained [20] by electrostatic interaction of ions and electrons. It was shown in a series of theoretical works [21 – 23] that the spectrum width and, indeed, T_i and m_j must be determined, the shape of the spectrum being dependent on the ratio T_e / T_i. This fact allowed to estimate the ratio T_e / T_i by the obtained scattering spectra, and also T_i, provided m_j is known. When applying this method for the determination of T_i, one of its shortcomings consists in the requirement of resorting to complementary data on the mass content of the ionosphere.

Let us briefly review the regularities of electron temperature variation, as they emerge from experiments.

DAILY VARIATIONS

The graphs of the daily temperature variations in the 200 – 250 km altitude range at 40° geomagnetic latitude, plotted according to data from Explorer-8 [24], Explorer-17 [25], Ariel-1 [26] and Alouette-1 [27], are presented in Fig. 1.

As follows from the above, measurements were conducted in various years by different methods, all unconditionally non-equivalent.

Altitude electron profiles were obtained in particular on Alouette-1 and the average temperature was determined, $(T_e + T_i)/2 = T_{eff}$, in the assumption that O^+ is the prevailing ion to 500 km height. Further it was estimated that $T_e = T_{eff}$. It is possible that the first assumption for 1962 is incorrect [26], while the second, as will be seen below, is doubtless invalid for the diurnal ionosphere; thus, the estimates of T_e based upon the data from Alouette-1 are less reliable than the direct measurements on the other satellites. This is clearly seen from Fig. 1, where according to data of direct measurements the daytime electron temperature is by about 1000° higher than the nighttime, whereas for Alouette-1 both, the night and daytime temperatures are about equal.

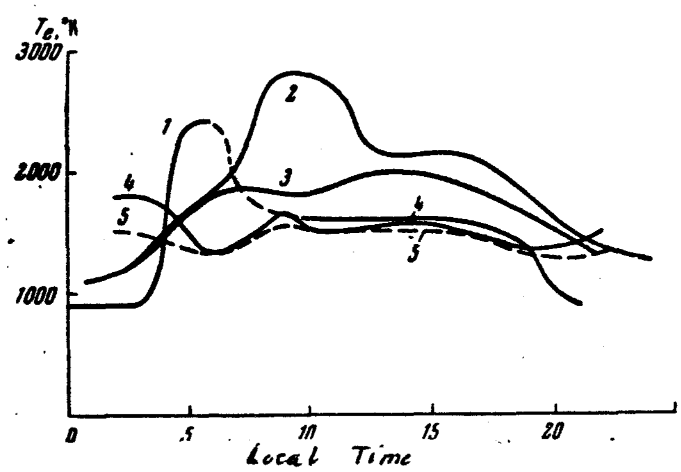

Fig. 1. - Dependence of T_e on the time of the day in the 200 — 250 km altitude range at 40° geomagnetic latitude according to data from various AES.
1 — Explorer-8; 2 — Explorer-17; 3 — Ariel — 1 ; 4, 5 — Alouette-1

A sharp maximum is noticeable on the 4 curves plotted in Fig. 1 for the daily course of T_e. Taking into account the difference in sunrise time, it is found that according to data from Explorer-8, Alouette-1 and Explorer-17, a sharp rise in electron temperature is noted at sunrise.

In the work [28] the morning maximum of T_e is explained in correspondence with formula (4) by the fact that at sunrise the concentration of charged particles is low, while the heat inflow rises sharply. Despite the fact that the utilization of (4) is not entirely rightful insamuch as formula (4) is derived for equilibrium and stationary conditions, as already noted above, it is deemed possible to agree with such a physical treatment. In reality, the concentration of "hot" photoelectrons increases sharply at once after sunrise and the ratio q/n_e of the concentration of these electrons to the total electron concentration in morning hours has its greatest value, at least at heights below the F-layer maximum. In the course of the day q/n_e is significantly smaller and it varies little with time; that is why T_e must not vary strongly through sunset.

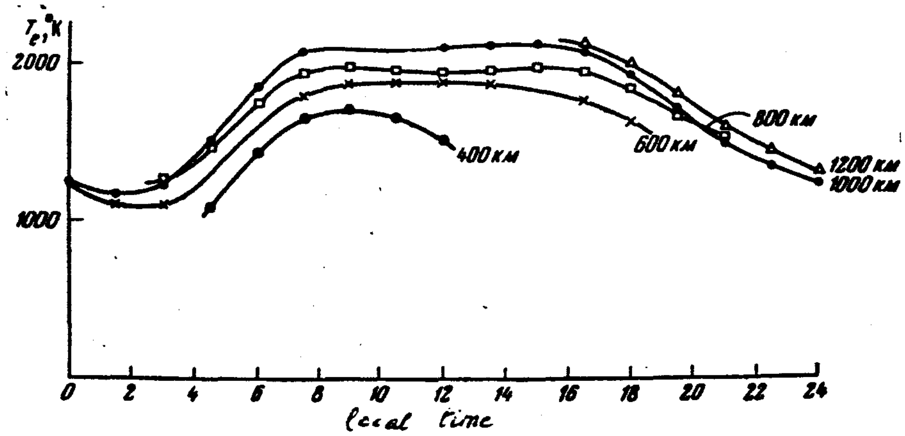

Fig. 2. - Dependence of electron temperature on the time of the day at various heights according to the data from AES Ariel-1

However, a somewhat different daily course of T_e, without sharp maximum in the sunrise period, was observed at the same geomagnetic latitude by AES Ariel-1. It is possible that this distinction appears as a consequence of the fact that the temperature data from Ariel-1 were obtained at points spatially dispersed by a distance of the order of 500 km. This is illustrated in Fig. 2 as a function of local time and according to [26]. It may be seen from the diagram that the electron temperature has a similar daily course at all altitudes.

Attention should however be drawn to the fact that in the work [26] the primary material, on the basis of which was carried out the separation of latitude, longitude and altitude effects acting on the parameters measured on the satellite, is represented without sufficient details, which hinders the reliable estimate of the results obtained with the help of Ariel-1.

Comparison of the values of electron temperatures measured in the experiments carried out at different years, with the temperarures of the neutral atmosphere, determined by measurements on satellites and rockets at heights below 1000 km [29, 30], shows that the diurnal electron temperatures always exceed T_{neutr}.

Inasmuch as there are exceedingly few measurements of T_i and since $T_i \approx T_{neutr}$, the results of simultaneous measurements of temperatures of neutral particles and electrons below the E-layer maximum are of great interest. - Such experiments were conducted in 1962 - 1964 on American rockets launched from Walloops Island (39° lat. N). T_e was measured by Langmuir sondes and T_{neutr} was determined by the results of measurements of molecular nitrogen with the aid of a mass-spectrometer [31].

The experiments were conducted ar various times of the day and are evidence of distinctions in the altitude profiles of T_e and T_{neutr}, corresponding to different illumination conditions; however, inasmuch as these results refer also to different seasons and years, they do no reflect the true daily variations.

Particular interest is offered by one of the experiments, in which the rocket was launched during a total solar eclipse. The electron temperatures measured during the eclipse are about twice lower than T_e corresponding to normal daytime profiles. This may constitute an obvious demonstration of the fact that the ultraviolet radiation is the fundamental source of heating for the F-layer.

We note here another, quite important result of these experiments, namely the corroboration of absence of temperature equilibrium in the ionosphere.

The diurnal electron temperatures measured in that experiment exceeded T_{neutr} in the altitude interval under investigation, with the maximum discrepancy of $\sim 1000^\circ$K (at $T_{neutr} = 800^\circ$K) – attained at 230 km. At night, T_e also exceeded T_{neutr} by about 150°K (at $T_{neutr} = 600^\circ$K) and a weak rise of T_e with height was observed.

In April 1964 T_e was also measured with the aid of Langmuir sondes on two rockets, launched in Mammaguir (Sahara) in twilight conditions (at sunrise and sunset), and T_{neutr} were measured by the emission spectra of Na and AlO, ejected at rocket flight). The results are plotted in Fig. 3. (See ref. [32]).

As may be seen from the diagram at heights ~ 270 km $T_e = T_{neutr}$, which isolates this result from those obtained in other experiments, where a maximum difference between T_e and T_{neutr} is usually observed in the same and neighboring heights.

On Cosmos-2, for example, on which a direct observation of T_i and not T_{neutr} was conducted at 300 km in daytime, it was found that $T_e = 3000°$ K and $T_i = 1300 \pm 200°$ K.

It is most probable of all that the discrepancy of these results is linked with the difference of latitudes and of the time of measurements.

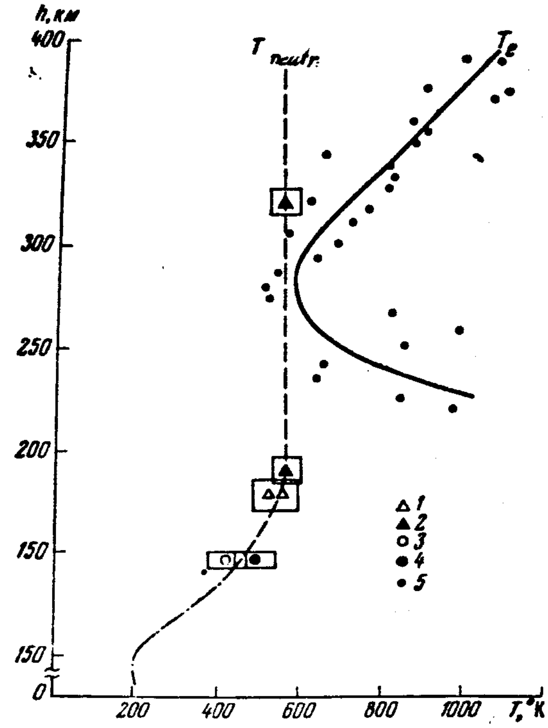

Fig. 3. - Results of simultaneous measurements of electron temperature and of that of neutral gas.

1 — T_{neutr} (Na) morn. 13 Apr. 1964;
2 — same for 11 Paril 1964.
3 — T_{neutr} (AlO) morn. 13 Apr. 1964·
4 — same for evening of 11 April
5 — T_e for morn. of 13 April 1964;
Solid line — T_e ; dashed 1 — T_{neut}
Dash-dotted line corresponds to the model T_{neutr} 1960 — 1964.

DIURNAL TEMPERATURES

1. - Altitude Course.- Interesting data on the altitude course of temperatures and of the temperature equilibrium have been obtained with the incoherent backscattering method. According to Evans [33], dating from 1961, at the latitude of $\sim 50°$ and in the 300 — 400 km altitude interval, $T_e / T_i = 1.6$; at the same time there is an altitude dependence, which the results of the experiment do not allow to interpret unambiguously. Evans assumes two possibilities :

1) T_e/T_i increases above 300 km while T_i = const;

2) T_e/T_i = const, while T_e and T_i increase with height.

According to Evans, the last dependence is more plausible, for it is corroborated by data on satellite acceleration revealing variations of daytime temperatures of the neutral gas, and consequently those of T_i [34]. Analysis of electron profiles obtained on Alouette-1 allows also to bring forth the same two assumptions [35].

The Evans data, obtained in 1963 experiments again admit two interpretations dependent on the assumed ionosphere mass content:

a) T_e and T_i increase with height;

b) T_e has a maximum at 450 km, and then decreases through 700 km; T_i increases comtinuously.

It should be noted that since $T_e - T_i$ depends relatively little on the mass content, but is dependent at the given height only on heat inflow and charged particle concentration [see (4)], the strong dependence on mass content of the determinations of T_e and T_i by the incoherent scattering is apparently evidence of the incorrectness of these determinations.

Bourdeau [36] assumes that the variations of the altitude course of temperatures in 1963 [23] by comparison with 1962 [33] may be explained by the variation of the level of solar activity.

It follows from Fig. 2, brought up above, that there exists an altitude temperature gradient, about equal to $\sim 0.5^\circ$K/km in the 1000 — 1200 km altitude range, and to about 1°K/km at lower altitudes. As is noted in [36] Willmore attempts to explain the altitude course of temperature obtained on Ariel-1 in accord with the theoretical model by Hanson [17]. If we compute the contribution Q of heat at various heights to 600 km according to the values of T_e and T_i obtained in the experiment and to formula (4), we shall find the result that the altitude course of Q is determined by the scale height of atomic oxygen. Hence Willmore concludes that the photoionization of atomic oxygen determines mainly the heat inflow in the ionosphere below 600 km and the altitude course of T_e detected on Ariel-1. Above 800 km the increase of T_e with height may be explained, according to Willmore, by heat inflow at the expense if photoelectron diffusion from below, provided the chief mechanism of heat losses is the conductance in the electron gas and not the collisions with positive ions.

It is interesting to note that contrary to Ariel-1, no variations of T_e with height were revealed on Explorer-8 (1960) at altitudes > 400 km [24].

Presented in Fig. 4 the measurements of T_e and T_i in coordinates (T, h) in various years and in different experiments [24 – 26, 37], including those in time of isolated launchings of Japansee and American rockets [38 – 41]. In spite of the imperfection of rocket experimental methods described in [41], the results of measurements of T_i are shown by dashes in Fig. 4, since these data are in accord with the altitude distribution of concentration obtained with the help of Langmuir sondes. Fig. 4 illustrates graphically the insufficiency of available information for ascertaining the altitude dependence of T_e and T_i in the upper ionosphere.

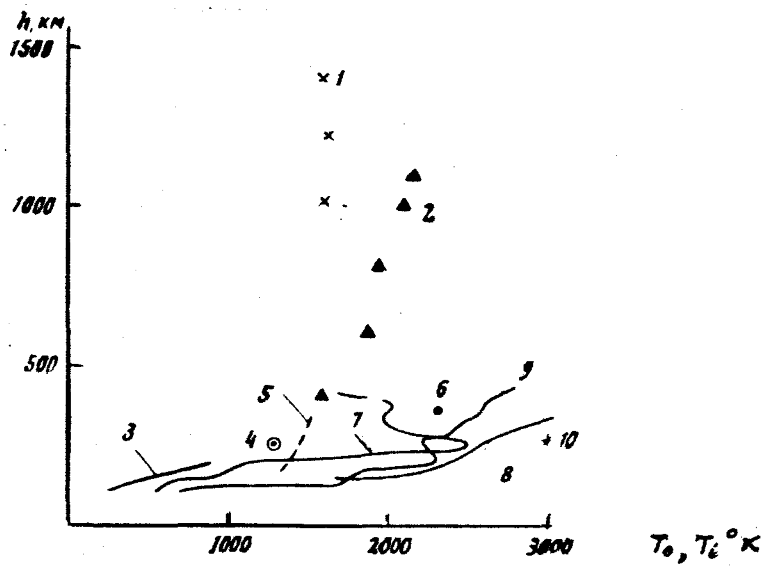

Fig. 4. - Altitude distributions of electron and ion temperatures according to data of various experiments.

1 – according to data from Explorer-8 (November 1960);
2 – " " " " Ariel-1 (April 1962);
3 – " " " Japanses rockets (March 1961);
4 – T_i " " " " Cosmos-2 (April 1962);
5 – T_i " " " USA rockets (July 1962);
6 – " " " Explorer-17 (April 1963);
7 – " " " rockets USA (March 1961);
8 – " " " " " (August 1962);
9 – " " " " " (August 1960);
10 – " " " Cosmos-2 (April 1962);

The points corresponding to data of Ariel-1 were borrowed from the curves represented in Fig. 2.

2. - Latitude Dependence.- As was established above, temperature equilibrium is absent in daytime at high latitudes. In the equatorial regions, according to data on incoherent scattering [42] of 1963, in the 200-350 km altitude range T_e/T_i is near 2 with maximum at 275 km; above 400 km $T_e/T_i \approx 1$, with the upper limit of this ratio being equal to 1.2.

The electron temperature increases with the latitude. Shown in Fig. 5 is the latitude course of T_e according to data from Ariel-1 [26] of 1962, and of Explorer-22 [43] (1964). The experiment on Explorer-22 was conducted under the most favorable conditions for ascertaining the latitude course of T_e. The satellite had an approximately circular orbit at 1000 km height and an inclination of 80°.

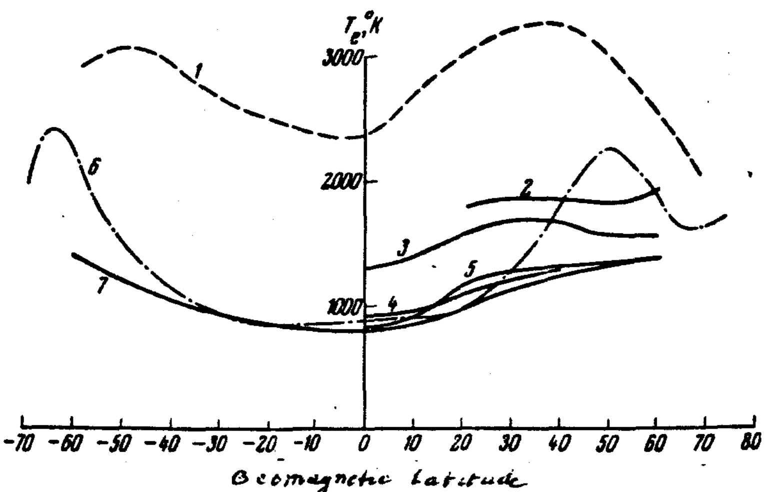

Fig. 5. - Latitude course of electron temperature according to data from Ariel-1 (solid curves) and Explorer-22 (dashed and dash-dotted lines).
1 — 1000 km, 12 - 15 00 hrs; 2 — 1000 km, 18 00 hrs; 3— 600 km, 12 00 hrs; 4 — 1200 km, 24 00 hrs; 5 — 400 km, 12 00 hrs; 6 — 1000 km, 03 00 hrs; 7 — 1000 km, 24 00 hrs (local time).

The maximum gradient of T_e was observed on Ariel-1 at latitudes ±20° and the mean latitude gradient in daytime was equal to 8° K on 1° latitude.

On the equator the daytime temperature at 400 km was equal to 900° K (Fig. 5) and at 60° latitude to 1400° K. It may be seen from Fig. 5 that the altitude temperature gradient was also observed on Ariel-1 in the eq atorial latitudes, being at the same time about identical for great heights as at high latitudes. (Observed on Ariel-1 was also a significant lateitude gradient of ion temperature, determined by peak widths corresponding to oxygen ions [55]).

According to data of Explorer-22, the latitude variations of electron temperature in daytime are still more significant than those shown by data from Ariel-1. The mean gradient is $\sim 20^{\circ}$ per degree latitude; at the same time in the winter hemisphere (Northern latitudes) the temperatures are higher, the variations with latitude are more significant and the maximum sets in at lower latitudes than in the Southern hemisphere. The daytime temperature on the equator at 1000 km altitude is $\sim 2400^{\circ}$ K. At 35 — 40° N. latitude T_e is about equal to 3400° K, while in the Southern hemisphere the maximum temperature of $\sim 3000^{\circ}$ corresponds to the latitude -50°S.

The increase of T_e with latitude was also revealed on Explorer-17 [44]. The maximum gradient of $\sim 20^{\circ}$ per degree of latitude (same as on Explorer-22) was observed at middle latitudes.

There are attempts to explain the latitude course of temperature according to theoretical models, by latitude variation of electron concentration at the given altitude [36, 43].

In accord with the Hanson and Dalgarno calculations [17, 18], in the F-layer, where the basic role in the cooling of electron gas is played by collisions with neutral particles, the thermal balance equation is written as follows :

$$Q = n_e n_{neutr} (T_e - T_{neutr}),$$

and the electron temperature must vary inversely-proportionally to electron concentration in the case when Q does not vary with latitude.

In the F_2-layer, and higher to 1000 km, where cooling takes place at the expense of interaction with ions, the electron temperature must vary inversely-proportionally to the square of electron concentration, as this follows from formula (4).

At great heights the electron temperature is determined by the conductance of the electron gas and the concentration of electrons — by diffusion processes, and T_e must not depend on n_e.

The latitude variations of altitude profiles of n_e are determined by the geomagnetic field, as it follows from measurements with the aid of the airborne ionospheric station Alouette-1. An equatorial anomaly in the distribution of n_e with latitude was in particular revealed with the aid of the latter. It was found that the latitude ionization maximum about from

10 00 to 22 00 hours local time is locates along the magnetic lines of force resting on the latitudes $\pm 15^{\circ}$ and rising to 1000 km height above the equator [35].

It may be shown that such a latitude course of electron concentration according to data of Alouette-1 and of electron temperature from Ariel-1 are both linked by a dependence forecast by the theoretical computations of Hanson [18] (formula (4)), provided the ultraviolet radiation and the mechanism of losses do not depend on latitude.

The above described correlations are basically fulfilled, as is made evident by the simultaneous variations of T_e and n_e on Explorer-22 [43] and Explorer-17 [44].

NIGHT TEMPERATURES

For the night hours the ratio $T_e / T_i \approx 1$ according to data on the incoherent scattering for equatorial latitudes.

According to Bowles [45], in 1962 on the equator $T_e \approx 600^{\circ}$ K at night. This figure is in accord with the data of Harris and Priester model [46].

The night temperatures also disclose a latitude course, rising with latitude increase. According to data of Ariel-1 [26] at 1000 km in the night time T_e rises from 800° K at the equator to values of 1400° K at 60° N.g.lat.

According to data from Explorer-22 the night temperature at 1000 km height in the 20 to 30° N. latitude interval is about constant and equal to 800° K, but increases nearly threefold in the 50 – 70° N.latitude range.

Evans points out that there is a small deflection for the night hours of temperature equilibrium in the F-region, with the value of the nighttime ratio T_e / T_i at 300 km altitude in the solar activity minimum being essentially dependent on the season. In the summer it is ~ 1.2, while in winter it may reach ~ 2 [33, 47].

According to measurement data of [26, 43, 48], this deflection becomes clearly expressed at nearing the high latitudes.

Nighttime rocket measurements at middle latitudes have shown that there is a small difference between T_e and T_{neutr} and a tendency of T_e to increase with height.

In order to explain such a night course of electron temperature we must assume that there exists a heat source at nighttime, whose intensity constitutes 30% of that of ultraviolet source [36]. One of the possible explanations of night temperatures in the F-layer is given in [19], as was already mentioned.

Another cause of night ionosphere heating may be the presence of electric fields detected by direct methods for the past few years [49, 50].

The assumption of electric fields as being sources of night ionosphere heating was also brought forth in the works [28, 31].

CONCLUSION

Thus, the coincidence of the above presented data on the temperatures of ions and electrons in the ionosphere entails the following conclusions.

1.- The temperature equilibrium in the ionosphere is absent; at the same time, deflections from equilibrium in daytime at F-layer height at all latitudes reach a substantial value ($T_e/T_i = 2$ and 3).

2.- At low latitudes in daytime and at great heights the ratio T_e/T_i — 1.1 — 1.3, while at high latitudes it may be greater ($\sim$1.6). It should be stressed that these data refer to a period near the solar activity maximum.

3.- The night temperatures of ions and electrons are about equal on the equator; at high latitudes, at nearing the aurora zone there is observed at the height of the F-layer a deflection from temperature equilibrium which may reach a significant value.

4.- The electron temperature increases with the latitude.

So far, the explanation of latitude dependence of electron temperature, clearly outlined in the experiments on Ariel-1 and Explorer-22, and indirectly corroborated by the incoherent scattering method, appears to be little satisfactory.

The explanation given in connection with the Hanson model is formal in essence, since so far it was not possible to compute theoretically the distribution of n_e with latitude. The theory, satisfactorily describing the equatorial anomaly is semiphenomenological and is based upon the hypothetical assumption that ambipolar diffusion in the ionosphere above the F-layer is possible only along the lines of force of the magnetic field, while the diffusion equilibrium is also sustained along them [51 — 54].

The explanation of the latitude course of temperature by difference in heat transfer conditions along the magnetic tubes of force at various latitudes still requires further calculations [19].

5.- Relative the altitude course of temperatures, the following may be stated.

According to data of rocket measurements in quiet and disturbed ionosphere the temperature T_e may vary with altitude rather significantly to height of 400 km; at the same time negative gradient are observed.

The question of altitude dependence of T_e and T_i above 400 km still remains open and it is quite indispensable to accumulate a new factual material for its solution. Experiments on satellites allow to obtain a great number of data; however, they have such shortcomings, whereby it is difficult to separate the altitude, longitude and latitude effects. That is why it is necessary to undertake launchings of altitude rockets with sounding measurements of electron temperature, this being the most reliable method for obtaining more accurate data on the altitude course of temperature.

6. - Measurements of ion temperature are so few that it is presently impossible to derive any conclusions on the regularities of T_i variations from them. In the future it will be necessary to carry out, alongside with measurements of electron temperature and of that of neutral components, experiments for the determination of the ion temperature, inasmuch as it follows from theoretical calculations that at heights above 1000 km, $T_i \neq T_{neutral}$.

7.- Comparison of calculation and experimental values of T_e and T_i attests to the necessity of broadening the direct measurements of ion and electron temperatures, and of accumulating information on such thermal sources, as the electrostatic fields, hydromagnetic waves and fluxes of charged energetic particles.

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*** THE END ***

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